Characterization of The Dynamic Behavior of LIGA Fabricated Beams

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1 ABSTRACT

LIGA manufacturing produces engineering components at micrometer to millimeter sizes and materials with extremely fine microstructure features, which enables the production of small, lightweight, and simplified devices for many potential applications. In order for LIGA microsystems to be properly designed, engineered, and packaged for application, their structural dynamic characteristics must be well understood. This paper describes exploratory experiments of some compliant LIGA microstructures in their potential application environments. Several high aspect ratio flexible beams were tested in fluids (including air, water and glycerol) and some were under large deflection conditions. Base excitation through a shaker as well as impulse loading was used as an input and the response was measured using a laser Doppler vibrometer (LDV). Experimental results of the tests conducted in air showed good agreement with finite element analysis that assumed an undamped model with linear material properties. Measurement made for large deflection showed the jump phenomenon, typical of the nonlinear dynamic behavior.

2 INTRODUCTION

LIGA manufacturing produces engineering components at micrometer to millimeter sizes. The process can use a large variety of materials and produce parts with a very high aspect ratio (>10), enabling the production of small, lightweight, and simplified devices for many potential applications. Unlike conventional structural-mechanical systems, compliant mechanisms are common in LIGA Microsystems. Flexible beams, instead of difficult to manufacture joints and hinges, are often used to enable large relative motions and to perform complex tasks with a minimum number of parts. External and internal disturbances, however, can cause the compliant mechanism to vibrate during operation and may result in undesirable mechanism performance. Hence, a proper energy dissipation or vibration isolation is needed, for example as a device immersed in a fluid. With the increase of the surface area to volume ratio of Microsystems, the surface forces may strongly influence their dynamic response. Little is known about the structural dynamic characteristics of LIGA Microsystems. Their performance can be adversely affected by the nonlinear geometric response, complex damping from fluid-structural interaction, and uncertain material and geometric properties. Therefore, experiments are needed to study and gain insight into some of these complex phenomena. Although experimental techniques have been developed for conventional structures, little work has been done at the LIGA length scale and methods are still being refined. This paper presents an exploratory experimental investigation of structural dynamic properties of several LIGA scale structures, specifically high aspect ratio microstructures (HARMST).

3 SPECIMENS AND EXPERIMENTAL SETUP

Three LIGA structures were studied for this investigation. They were cantilever-mass, cantilever-ring, and curved spring, shown in Figures 1-3, respectively. All are electrodeposited nickel manufactured from the LIGA process. In Figure 1, the cantilever is 0.15 mm wide, 1.5 mm thick, and 8.4 mm long. The mass is a cylinder with a radius of 0.6 mm and thickness of 1.5 mm. The center of the cylinder is 9.0 mm from the base of the cantilever. The structure shown in Figure 2 has two curved beams. The width and thickness of these curved beams are 0.15 and

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1.5 mm, respectively. The small cantilever shown in Figure 3 is 0.02 mm wide, 0.25 mm thickness, and 6.4 mm long. The center of the ring is 7.0 mm from the base of the cantilever with inside and outside radii of 0.2 and 0.6 mm, respectively, and a thickness of 0.25 mm. The thickness-to-width ratio of all these structures is equal to or greater than 10, and the length-to-thickness ratio is at least 5. The deformation of these beams is primarily in-plane.

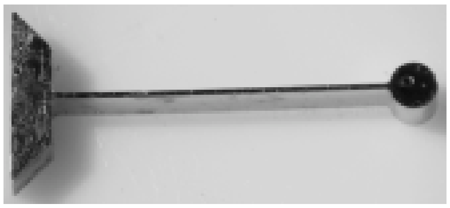


Figure 1. Cantilever-mass.

Figure 2. Curved spring.

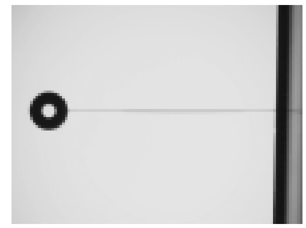


Figure 3. Cantilever-ring.

A non-contact vibration measurement technique is used to obtain an accurate dynamic response of the LIGA structures. The experimental setup consists of a function generator, mounting fixture, shaker, fluid container, LDV, and data acquisition unit (see Figure 4). The base of a cantilever is firmly clamped to one end of the mounting fixture, and the other end of the fixture is fastened to the shaker. The function generator outputs a sinusoidal signal that controls the amplitude and frequency of the shaker. The LDV measures the velocity component that is parallel to the laser beam. By aiming the LDV at the vibrating object, the surface velocity of the laser reflected spot is acquired. The velocity signal is digitized, displayed and recorded on the data acquisition unit. Velocities are measured at least two locations in the steady-state vibration experiment: one is on the fixture that represents the input excitation at the base of the LIGA beam, and others are points on the LIGA beam denoting the output response of the structure. The current setup remains accurate even when the laser spot size (about 1 mm diameter) is larger than the object (e.g., the thickness of the small cantilever beam) and with a container wall and fluid in the laser path. This is due to the LDV only requiring a portion of the original light signal to be reflected back.

4 STEADY STATE VIBRATION IN VISCOUS ENVIRONMENT

Using the setup described above, LIGA beams were submerged in fluid in a clear container by a C-shape mounting fixture. Tests were conducted in three fluids with very different viscosities, air (0.017 mPa s), water (0.8909 mPa s), and glycerol (10 mPa s). Figure 5 shows the cantilever-mass specimen submerged in water. The trace of the laser path in the fluid is visible; one end is on the thick side of the beam and the other is on the container wall. With proper alignment, the transparent media between the LIGA structure and the LDV, such as the fluid and container wall, do not affect the velocity measurement.

During this experiment, the LIGA structure was subjected to a sinusoidal excitation at its base, $z = Z\sin\omega t$. When the response became steady state, the magnitudes of the base velocity, $\dot{Z}$, and the velocity at the end of the beam, $\dot{Y}$, were recorded. The magnitudes of the base displacement, $Z = \dot{Z}/\omega$, and the beam deflection, $Y = \dot{Y}/\omega$, were then calculated from the corresponding frequency and velocity. The measurement procedure was repeated over a range of frequencies and the dimensionless response amplitude, or transmissibility Y/Z, versus frequency curve of the structure was constructed. The natural frequencies correspond to the maxima of the curve.

Experimental results of cantilever-mass, curved beam and small cantilever-ring are shown in Figure 6 - 8, respectively. Figure 6 shows that the natural frequency of the cantilever-mass is 690 Hz in air, 605 Hz in water, and 510 Hz in glycerol. The natural frequency and amplitude of vibration decrease when the fluid viscosity increases. The same trend is observed in Figures 7 and 8, where the natural frequencies are labeled.

Unfortunately, for the curved beam and the small cantilever-ring structure in the glycerol environment, the signal to noise ratio was too low to record accurate data and hence those cases were not plotted. Due to the limitation of frequency of the shaker, only the fundamental mode was detected for the cantilever-mass and curved beam structures. The shaker was able to generate the second resonance mode of the small cantilever-ring structure.

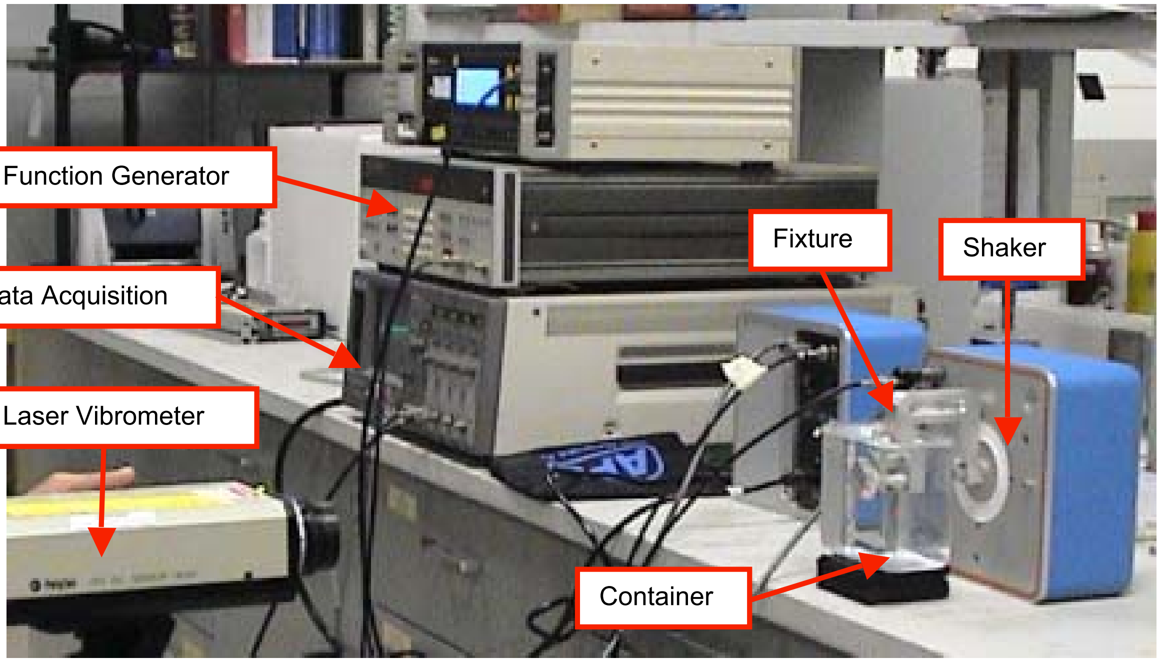


Figure 4. Experimental Setup

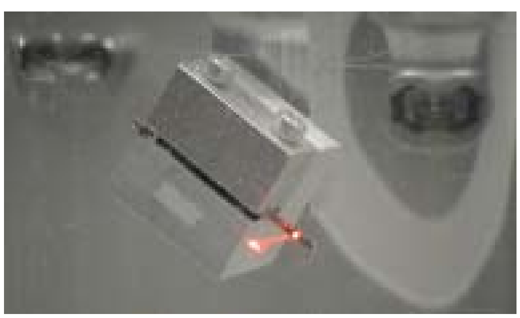


Figure 5. Cantilever-mass specimen submerged in water. The laser spot on the beam indicates the location of velocity measurement.

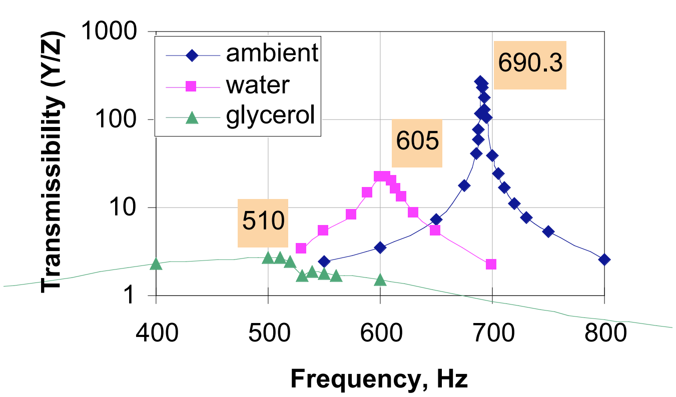


Figure 6 Transmissibility of the cantilever-mass structure.

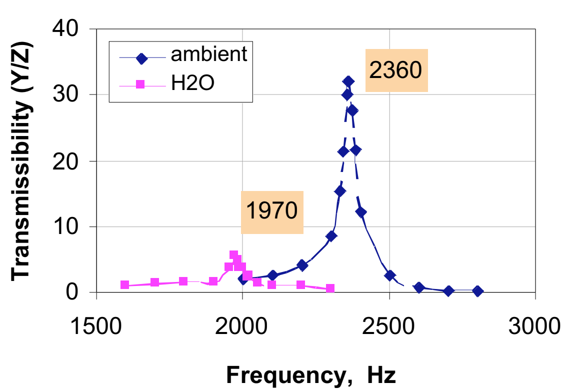
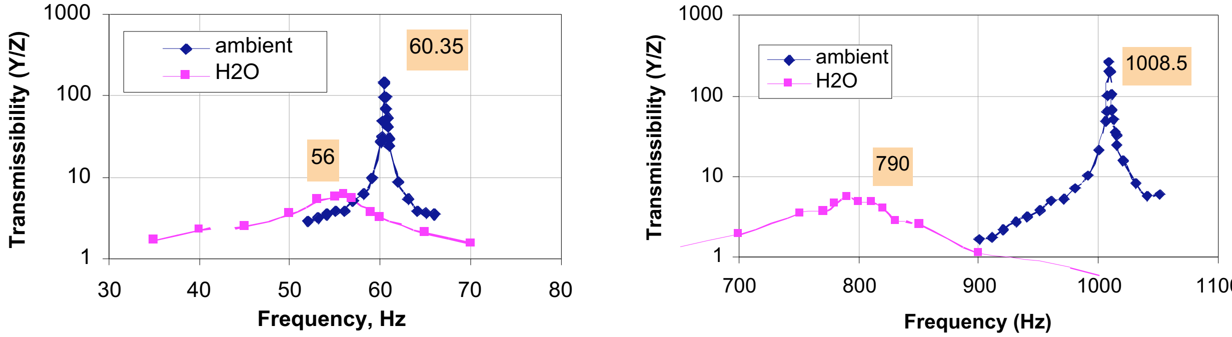


Figure 7 Transmissibility of the curved beam.



(a) (b)

Figure 8 Transmissibility of the small cantilever-ring structure, (a) 1st transverse mode, (b) 1st torsional mode.

The results for all the structures are shown in Table 1. The frequency shift depends not only on the viscosity of the fluid but also system parameters such as mass and geometry.

Table 1 Results of LIGA structures submerged in fluid

LIGA Structure	Condition	Mode	Beam Displacement Amplitude (μm)	Frequency (Hz)
Cantilever-Mass	water	1st transverse	15	605
	glycerol	1st transverse	1.5	510
Curved Spring	water	1st transverse	0.3	1970
Small Cantilever-Ring	water	1st transverse	6.8	56
		1st torsional	0.095	790

5 IMPACT TESTING AND FINITE ELEMENT SIMULATIONS

An impact testing method can also be used to obtain the vibration characteristics of a structure. Different from the steady state sinusoidal excitation method, which finds the natural frequency by stepping through the frequency range, impact loading creates a spectrum of natural frequencies and the range of frequencies extends beyond that produced with the shaker. The experimental setup is similar to the one mentioned earlier, shown in Figure 4. The only difference is that instead of using a shaker, the fixture is placed in a clamp. A hammer applies an arbitrary pulse shape, which contains all frequencies to a greater or lesser extent. The structural response signal is digitized and recorded, and natural frequencies of the structure are obtained by taking a fast Fourier transform (FFT) of the signal.

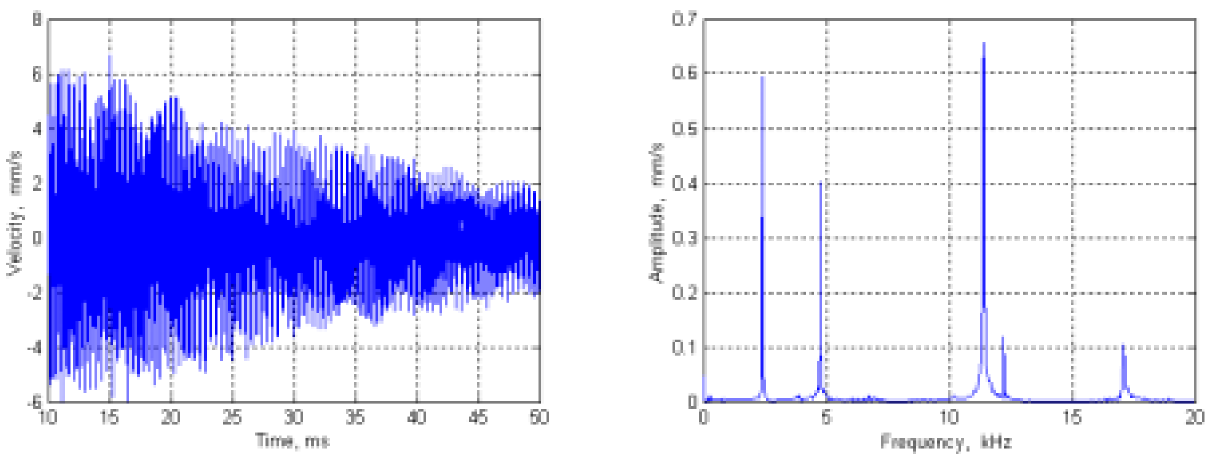
Impact experiments were conducted in air only. Figure 9 shows a typical impact response signal from a spot close to the end of the vibrating curved spring and its corresponding spectrum of natural frequencies. The sampling rate of the signal was 2 MHz. All three structures were tested. Experimental results are shown in Table 2, which also includes the results of the shaker experiments and finite element (FE) analyses. For the curved beam, the impact experiment data does not have the resolution to differentiate the second and third mode found in the FE analysis. The specimen was then tested in a different stead-state setup, which used a microscope based LDV and a shaker with a higher frequency range. The natural frequencies of the second and third modes were measured at 4740 and 4760 Hz, respectively.

To compute natural the frequencies of these structures in the air environment, the FE analysis assumes the material is linear elastic and without damping. Nominal material constants of electrodeposited nickel (Young's modulus = 200 GPa, Poisson ratio = 0.33, and density = 8880 kg/m^3) and specimen dimensions (described in Section 3) are used. The FE results correlate well with the experimental data. Uncertainties may arise from geometry and material variations.

Table 2 Comparison of vibration experiments in air and finite element computation.

Structure	Resonance Frequency, Hz			Mode
	steady-state	impact	FE	
Cantilever-mass	690	694	693	transverse
	-	6,009	6,334	transverse
	-	9,746	8,562	torsional
	-	17,831	13,364	transverse
Curved spring	2,360	2,400	2,400	transverse
	4,740*	4,700	4,500	torsional
	4,760*	4,700	4,700	transverse
	-	11,370	11,200	torsional
Cantilever-ring	61	59	57	transverse
	1,008	1,014	935	torsional
	-	1,490	1,127	transverse

* Using microscope-based LDV setup.



(a) (b)

Figure 9 Impulse loading of the curved beam: (a) velocity response at the end, and (b) frequency spectrum.

6 NONLINEAR BEHAVIOR UNDER LARGE DEFLECTION

In the experiments and analysis described above, beam deflections were typically small, i.e., they were comparable to the width of the beam. The deformation was within the elastic limit of the material and the slope of deflection was nearly zero ($dy/dx<<1$). Under these conditions, the beam's load and deflection relationship was linear.

In many micro-scale applications, thin beams are commonly used in flexure-based compliant mechanisms or as flexure hinges. In such cases the deflection is much larger than its width, and the small deflection assumption is no longer valid. When the slope of deflection is not negligible or the material behavior deviates from linearly elastic, the governing relation between the load and deflection of a beam becomes nonlinear. The nonlinear structural dynamic behaviors of flexures need to be considered.

Using the same setup displayed in Figure 4, two experiments were performed to investigate the effect of large deflection on the dynamic behavior of LIGA beams. In the first experiment, the small cantilever-mass was subjected to various levels of sinusoidal excitation around its fundamental resonance frequency. For a fixed value of Z, the resonance frequency was determined from the maximum velocity $\dot{Y}$ by varying the excitation frequency. The deflection at resonance, Y, was then calculated from the corresponding frequency and velocity. Experimental parameters and results are listed in Table 3. The data shows a downward shift of the resonant frequency as the level of excitation is raised. This is clear indication that the response is nonlinear and it is a softening system with decreasing effective stiffness [1].

Table 3 Resonance frequencies of the small cantilever-mass at various amplitudes of deflection

Shaker		Beam		Transmissibility	Resonance
Velocity (mm/s)	Displacement Z (mm.)	Velocity (mm/s)	Displacement Y (mm.)	Y/Z	Frequency (Hz)
0.45	0.0012	18	0.05	40	59.00
0.64	0.0017	67	0.18	104	58.92
0.78	0.0021	112	0.30	143	58.85
1.27	0.0034	180	0.49	142	58.79
2.05	0.0056	239	0.65	117	58.72
2.62	0.0071	289	0.78	110	58.69
2.82	0.0076	336	0.91	119	58.66
5.89	0.0160	474	1.29	80	58.62
8.51	0.0231	610	1.66	72	58.57
10.50	0.0286	763	2.07	73	58.49
12.35	0.0337	910	2.48	74	58.40

In the second experiment, displacement responses were obtained using steady-state sinusoidal excitation. A different specimen, small cantilever-ring #2, was used. At each frequency step, the shaker generated a constant amplitude sine wave, $z = Z \sin \omega t$. The displacement response was allowed to reach a steady-state condition and the amplitude of deflection, Y, at the excitation frequency was determined. Two exciting amplitudes, Z = 0.00023 and 0.0074 mm, were applied in this study.

The displacement response for Z = 0.00023 mm is shown in Figure 10. The symmetry of the response curve means the force displacement characteristics of the beam are linear. At the resonance frequency, 57.58 Hz, the steady-state amplitude is about 0.037 mm at the end of the beam. Notice that the width of the beam is 0.02 mm, so the deflection can be assumed as small and the dynamic response is linear. A picture of the vibrating beam is shown in Figure 11. The fuzzy contour of the ring and the beam displays the magnitude of vibration.

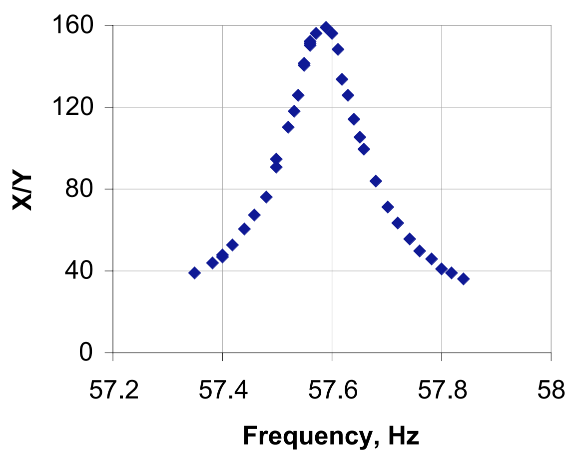


Figure 10 The 1st bending mode of small cantilever-ring #2 with base excitation Z=0.00023mm.

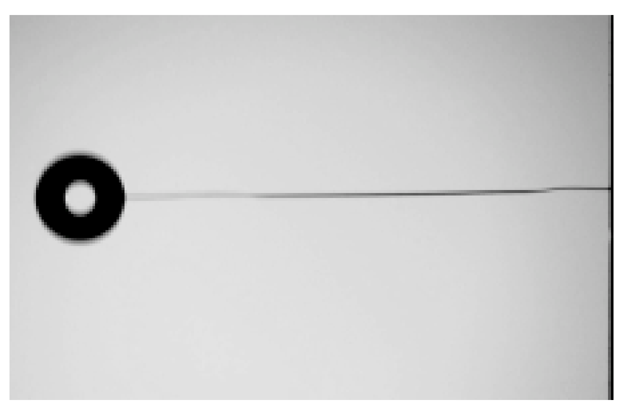
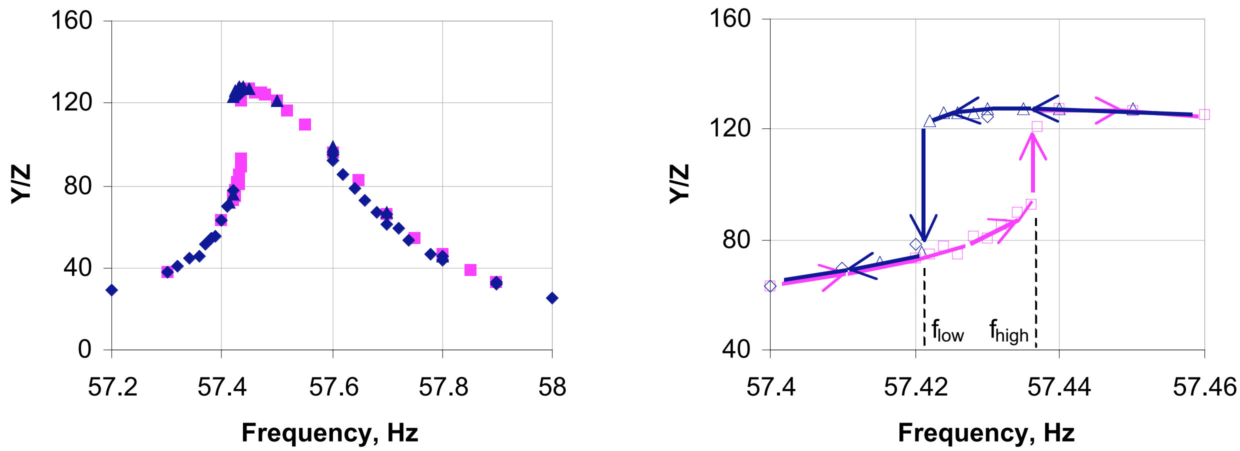


Figure 11. Small cantilever-ring #2 vibrating at 57.58 Hz with base excitation Z=0.00023mm.

Small beam #2 was then subjected to a stepped-sine excitation at a much larger magnitude, Z = 0.0074 mm. The displacement response curve is shown in Figure 12(a). The curve is asymmetric and bends towards the left, exhibiting the typical nonlinear characteristics of a softening system. At the resonance frequency, approximately 57.47 Hz, the steady-state beam displacement at the ring end is about 0.93 mm, which is much larger than the width of the beam. The jump phenomenon occurs to the left of the peak, the portion of the curve is expanded in figure 12(b). With increasing excitation frequency, the amplitude gradually increases until f_{high}, 57.437 Hz, is reached. At this point it suddenly jumps to a larger value. When decreasing the frequency from a frequency greater than f_{high}, the amplitude suddenly drops to a smaller value at f_{low}, 57.421 Hz. Figure 13 shows the oscillating beam at 57.46 Hz, where the envelope of deflection is observed.



(a) (b)

Figure 12 The 1st bending mode of small cantilever-ring #2 with base excitation Z=0.0074 mm.

Figure 13 Small cantilever-ring #2 vibrating at 57.46 Hz with base excitation Z=0.0074 mm.

7 SUMMARY AND CONCLUSIONS

This paper presents an experimental study of structural dynamics of LIGA HARMST. The experimental technique based on LDV measurements was shown to be effective in both air and transparent liquids. Displacement response curves and spectra of natural frequencies of LIGA structures were obtained.

The effect of fluid on the LIGA structures was studied for various viscosities and beam geometries. The following conclusions are drawn from the experimental results: (1) Natural frequencies and amplitude of vibration decrease when the fluid viscosity increases. (2) The shift of resonance frequency depends not only on the viscosity of the fluid but also system parameters such as mass and geometry.

The dynamics of LIGA structures in air were modeled using linear FE analysis. Experimental results and FE predictions correlate well. The FE results helped to guide the experiments and distinguish the mode shape of vibration for each natural frequency. Future research will include modeling these structures in liquids, i.e. coupled structural and fluid dynamics. The fluid structure interaction is a complicated phenomenon. More experiments are needed to generate data for higher vibration modes and different geometries.

The cantilever-ring specimen showed structural dynamic nonlinearity. Compliant mechanisms with large magnitude motion will require further investigation.

8 ACKNOWLEDGMENTS

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[1] Worden, K. and Tomlinson, G.R., *Nonlinearity in Structural Dynamics*, Institute of Physics Publishing, 2001.